

VICTORIAN COASTAL GEOMORPHOLOGY

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ABSTRACT: The geomorphology of the Victorian coast is reviewed in terms of the geological background, the processes at work in the shore and nearshore zones, and the effects of late Quaternary sea level changes. Cliffs and shore platforms, beaches and associated features, and inlets, estuaries and lagoons are each considered in relation to the processes that have shaped them, and attention is given to key problems, notably the need to quantify coastal processes, to establish more precisely the sequence of Holocene sea level changes relative to the land margin (in particular the question of a higher Holocene sea level episode), to elucidate the processes, particularly induration, that have contributed to the shaping of shore platforms, and to establish the origin and mode of delivery of sandy sediments to the present coast.

INTRODUCTION

The study of coastal geomorphology in Victoria has evolved from geological accounts of coastal regions, many of which included descriptions of coastal features. Notable contributions came from Baker (1943, 1944, 1950, 1958) on the cliffed coasts of the Port Campbell district, Boutakoff (1963) on the Portland area, Edwards (1942, 1945, 1962) on San Remo, Phillip Island and the Lorne district, Jenkin (1968) on south-east Gippsland, and Keble (1950) on the Mornington Peninsula. Inevitably, some of the geomorphological material in these reports is outdated in terms of modern concepts, but much useful information has been summarised in the *Regional Guide to Victorian Geology* (McAndrew & Marsden 1973) and the *Geology of Victoria* (Douglas & Ferguson 1976).

More specific accounts of geomorphological features on the Victorian coast have been published by Gill, who in the Port Fairy-Warrnambool district (Gill 1967a) and elsewhere has endeavoured to trace the sequence of late Quaternary changes of sea level and the responses of coastal landforms to these changes. There have been discussions of the evolution of shore platforms (Jutson 1940, 1948, 1949a, b, 1950, 1954; Hills 1949, 1971, 1972; Edwards 1951; Gill 1967b, 1972a, b), and investigations of the nature and origin of beach sediments (Baker 1945; Beasley 1957, 1969, 1971, 1972; Bird 1970; Gell 1978) and related dune systems (Coulson 1940; Coutts 1967;

Whincup 1944). Sectors that have received attention include Port Phillip (Hills 1940, Keble 1946, Bowler 1966), Western Port (Jenkin 1962, Marsden & Mallett 1975, Bird & Barson 1975), and the Gippsland Lakes (Bird 1978).

The literature on the coastal geomorphology of Victoria is thus substantial, this being among the more intensively documented sectors of the world's coastline; yet there is still much work to be done. The emphasis so far has been on the interpretation of coastal landforms in terms of hypotheses of sea level change, deduced patterns of sediment movement, and inferred processes of weathering, erosion and deposition. Much more data is needed on the regimes of waves, tides and currents in Victorian coastal waters (including estuary and lagoon systems); on the physical, chemical and biological processes at work on rocky shores; on the quantities of sediment moving onshore, offshore and alongshore; and on the effects of local climate, especially temperature, rainfall, and wind action, on the evolution of coastal dunes and their stabilisation by vegetation. Nevertheless, the broad relationships between coastal landforms and the processes at work on them have been described, and it will be useful to summarise these and discuss some of the problems that require further consideration.

The landforms of the Victorian coast (Fig. 1) include a variety of geomorphological features, ranging from the precipitous limestone cliffs of Port Campbell and the steep granitic slopes of

Wilson's Promontory to the long sandy surf beaches of the Gippsland coast and the low-lying mangrove-fringed salt marshes on the shores of Western Port and Corner Inlet (Bird 1977a). This diversity is related partly to geological factors and partly to contrasts in coastal processes, particularly wave action, which is much stronger on the outer, oceanic coastline than in the more sheltered inlets and embayments.

GEOLOGICAL BACKGROUND

The coastal outlines of Victoria have been much influenced by the uplift of the Otway Ranges, the Mornington Peninsula, and the South Gippsland Highlands, and the subsidence of the Western District, the Port Phillip and Western Port sunkenlands, the Corner Inlet depression, and the structural trough that underlies the Latrobe Valley and extends beneath the Gippsland Lakes to the east. Wilson's Promontory stands out as a much-dissected intrusion of Devonian granite to the south of the Corner Inlet depression, and in the far east of the state the coastline truncates the Palaeozoic formations of the Eastern Highlands of Australia, which here show a north-south trend in the folding and faulting of the rocks and the pattern of granitic intrusions (Fig. 2).

Table 1 shows the geological formations exposed on the coast. The oldest are Cambrian greenstones, which outcrop in cliffs near Cape Liptrap, in the core of one of the anticlinal axes of the uplifted South Gippsland Highlands. Cretaceous formations are exposed in cliffed headlands between Inverloch and San Remo, and on the steep coast of the Otway Ranges, where they are flanked to east and west by outcrops of Tertiary sediments, which also extend to the shores of Port Phillip and Western Port. Older Volcanics (Eocene to Miocene) emerge on the southern coast of Mornington Peninsula and dominate the shores of Phillip Island, while Newer Volcanics (Plio-Pleistocene) border the western shores of Port Phillip Bay and outcrop on the coast of the Western District at Portland and Port Fairy. Quaternary dune formations are mainly calcareous west of Wilson's Promontory, including the partially lithified dune calcarenites of the Nepean Peninsula and the Warrnambool coast, and quartzose to the east, where they include the multiple barrier formations of the East Gippsland coast. Finally, Holocene shore sediments, mainly sand and mud, are extensive within Western Port and Corner Inlet.

COASTAL PROCESSES

There are marked variations in the nature and intensity of processes at work along the Victorian coast. Much of the outer coastline is exposed to ocean swell derived from distant storm activity in the Southern Ocean. A prevailing south-westerly swell, with wave periods of 12 to 16 seconds, moves in through the western approaches to Bass Strait to break upon the shoreline west of Wilson's Promontory. In the eastern part of Bass Strait this swell mingles with a generally weaker south to south-easterly swell which has been transmitted through the sea east of Tasmania, and which moves in towards the Ninety Mile Beach and the predominantly sandy shoreline eastward to Cape Howe (Fig. 3).

The most vigorous storm waves in coastal waters are those generated by south-westerly gales, which break heavily on shores that face this direction, notably on the Portland promontory, the coast between Warrnambool and Cape Otway, and the headlands at Cape Schanck and Cape Liptrap. These are classified as 'high wave energy' sectors (Plate 1). They show bold, eroding cliffs and long sweeping sandy surf beaches which occupy curved embayments, the shape of which is determined by patterns of refracted ocean waves. Occasionally very large waves break against the high cliffs of the Port Campbell coast. Baker (1934) showed how storm waves at Broken Head, near Port Campbell, attain heights of up to 30 m above sea level: the cliff-top bench is awash as they break, then water pours back down the cliff face. The extreme vigour of wave attack on this coast is related to the fact that the adjacent shelf is narrow and relatively steeply shelving (Fig. 4); farther east, as the shelf widens, there is some reduction in the energy of waves reaching the shoreline, but it is still sufficient to produce heavy breakers on rocky shores, and the large 'surfing' waves that move in to Bell's Beach near Torquay, Gunnamatta, and Woolamai Beach on Phillip Island.

In the lee of headlands, and on the eastern shores of Wilson's Promontory, the prevailing south-westerly waves are weakened by refraction, and waves produced by the less frequent easterly winds, which blow mainly during the summer, are less vigorous. Consequently, these are 'moderate wave energy' sectors, with cliffing less pronounced, and coastal slopes in places vegetated down almost to high tide level.

Port Phillip, Western Port and Corner Inlet are penetrated only to a limited extent by ocean swell. Their shores are subject to waves generated by

TABLE I.
SUMMARY OF VICTORIAN COASTAL GEOLOGY

<i>Era</i>	<i>Period</i>	<i>Age m.yr.</i>	<i>Epoch</i>	<i>Coastal Geology</i>
CAINOZOIC	Quaternary		Holocene	Modern beaches, dunes, salt marshes Swamp peats, especially Western Port Tower Hill tuff Tyrendarra lava flow
			Pleistocene	Dune calcarenites mainly west of Wilson's Promontory Quartzose sands of Gippsland coast Quartzose sands of Port Phillip and Western Port Silty clays of the Bellarine Peninsula Older alluvium in bays and inlets Newer Basalt of Portland area and the Western District, extending south of Geelong and to the west coast of Port Phillip
	Tertiary	2	Pliocene	Ferruginous sands and sandstones (e.g. Baxter Sandstone) around Port Phillip and Western Port, and in East Gippsland Maretimo clays and early Newer Basalts in the Portland district
		7	Miocene	Balcombe Clay on the Mornington Peninsula Fyansford Clay and Curlewis Limestone on the Bellarine Peninsula Clays and sandy limestones at Torquay
				Clays near Princetown overlain by the Port Campbell Limestone, extending west to the Warrnambool district Portland Limestone Final flows of the Older Basalt
		26	Oligocene	Point Addis Formation, passing laterally from limestone to clay near Torquay, and resting on the Angahook Formation, which shows lateral transition from sand and clay at Anglesea through volcanic rocks at Airey's Inlet to limestones near Torquay Some Older Basalt
		38		Anglesea Sand; with organic sandy beds at Demon's Bluff Major Older Basalt flows of south-east Mornington Peninsula and Phillip Island
		54	Palaeocene	Eastern View Coal Measures at and west of Anglesea Grits, sandstones and clays between Moonlight Head and the mouth of the Gellibrand River
		65		
	Cretaceous			Sandstones (arkoses) and mudstones of Otways and South Gippsland (San Remo; Kilcunda; Cape Paterson-Anderson's Inlet), with minor outcrops in Port Phillip and Western Port
		136		

MESOZOIC	Jurassic			
	Triassic	195		
	Permian	225		Not represented
	Carboniferous	280		
PALAEOZOIC		345		
	Devonian			Intruded granites of Wilson's Promontory, Cape Woolamai, East Gippland, and granodiorites of the Mornington Peninsula Liptrap Formation at Cape Liptrap, and Bell Point and Waratah Limestones at Walkerville
		395		
	Silurian			Sandstone Island and Golden Point, Western Port
		440		
	Ordovician			Limestones and shales near Walkerville Shales and sandstones of the East Gippsland capes
		500		
	Cambrian			Greenstones near Cape Liptrap
PRE-CAMBRIAN		570		
				Not represented

winds blowing over short fetches within these bays, waves with typical periods of between 5 and 8 seconds. The prevalence of westerly winds produces stronger wave action on the eastern shores, which are in places subject to moderate wave energy, sufficient to have cut cliffs in sandstones and weathered granite and basaltic rocks (Plate 2). The more sheltered western shores have low wave energy conditions, with a more subdued topography, only limited cliffing and extensive development of depositional features, including sandy beaches, cusps, and spits, as well as salt marsh and mangrove fringes. The bay shorelines thus have a more intricate configuration than that of the high-energy oceanic coasts.

Other variations in coastal morphology are related to contrasts in tide range (Easton 1970). Tides in Victorian coastal waters are the outcome of westward movements through Bass Strait and around the southern and western shores of Tasmania. Mean spring tide ranges vary from less than a metre on the coasts of East Gippsland and the Western District to more than 2 m around Wilson's Promontory. At Point Lonsdale the mean spring tide range is 1.1 m, but it diminishes inside Port Phillip because the narrow gap between Heads impedes the inflow and outflow of tidal water. By contrast, tide ranges are augmented in Western Port, rising from 1.3 m at

Flinders to 2.3 m at Stony Point and over 3 m north of French Island (Fig. 1). Little is known of the tides in and around Corner Inlet.

The extent of the inter-tidal zone is related partly to tide range and partly to the transverse gradient of the shore. On the ocean coast the area exposed at low tide averages 50 m in width, some sectors being rocky and others sandy. Within Port Phillip the inter-tidal zone (28 km²) is generally about 30 m wide, also rocky and sandy, except for some muddy areas in Swan Bay and Corio Bay. Western Port has a much larger inter-tidal area (270 km²) with broad sandy and muddy areas exposed at low tide, particularly in the northern part of the bay where the ebb divides on either side of the tidal watershed between Lang Lang and French Island (Miles 1976). In Corner Inlet and behind the sandy islands off Port Albert the inter-tidal zone has an area of about 180 km², and in Anderson's Inlet, the estuary of Tarwin River, 16 sq. km of sand and mud flats are exposed at low tide. In all, Victoria has about 600 km² of inter-tidal land, the features of which await more detailed investigation.

Where the tidal range is small, tidal currents are weak, and have little effect on the erosion or transportation of coastal sea floor sediment, but where the range is large, and especially where the tide moves in and out of narrow straits, the

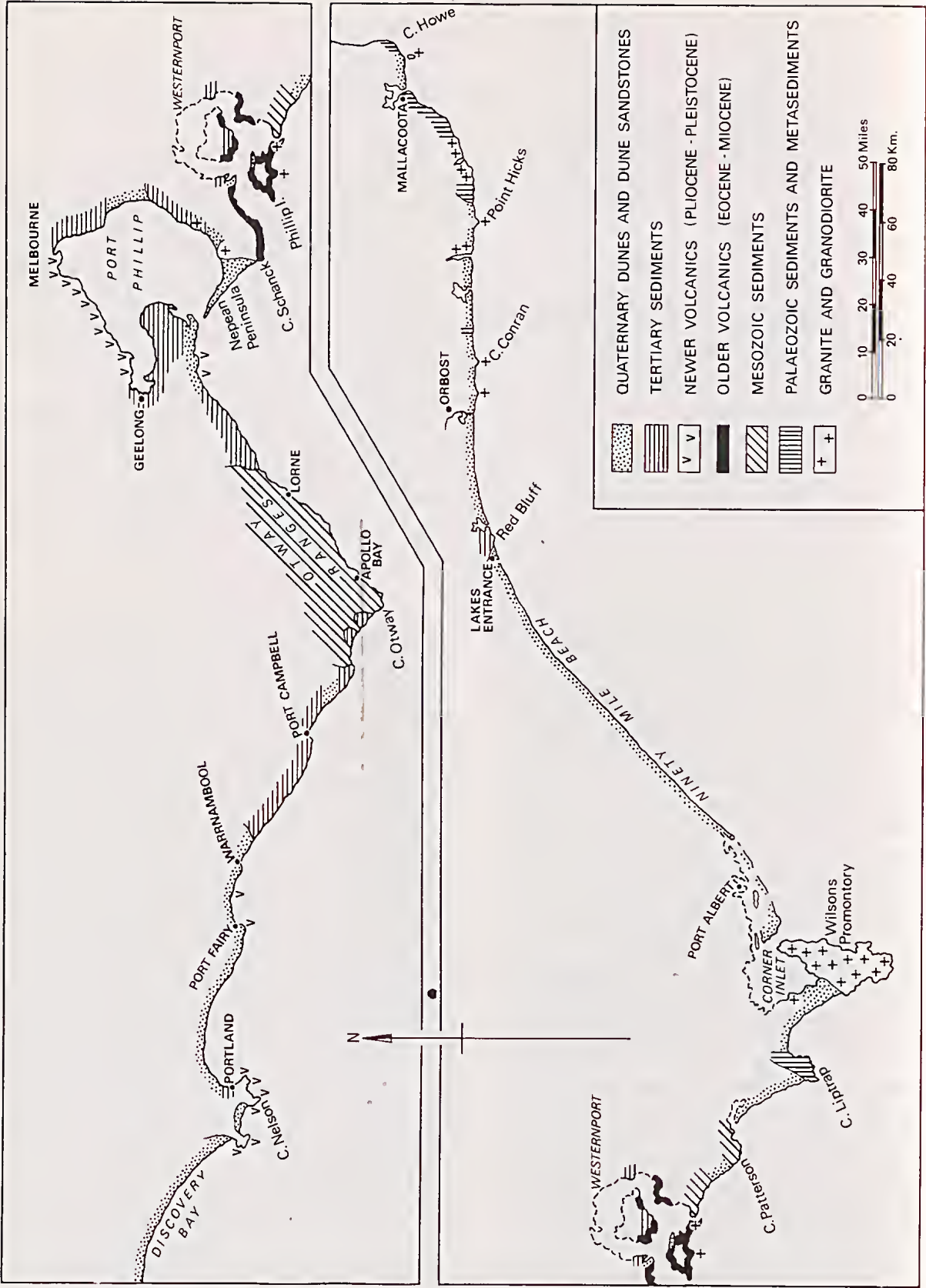


Fig. 2—Coastal geology of Victoria

associated currents may be strong enough to have direct or indirect effects on coastal morphology. Although the entrance has been widened and deepened by blasting, tidal currents through Port Phillip Heads still attain 10 to 15 km/hr (Australia Pilot, 1969), and in the shallow southern parts of Port Phillip there is a 'tidal delta' of shoals separated by diverging channels (Keble 1946). Shoal and channel topography is also found in Western Port, particularly in the north, where a tide range of more than 3 m generates strong currents as the sea rises and falls across broad intertidal mudflats. Tidal scour is strong in the narrow eastern entrance to this bay at San Remo, and tidally-scoured channels can also be seen in the sandy entrances to Anderson's Inlet, Corner Inlet, and the gaps between the sandy barrier islands off Port Albert. There are also tidal currents through the artificial entrance to the Gippsland Lakes, where the topography of the floor of Lake King shows giant ripples due to tidal scour (Bird 1978).

Tidal currents can influence shoreline features both directly, where the lateral shift of a scoured channel towards the shore leads to undercutting, or where the migration of such a channel away from the shore results in shallowing and sediment deposition, and indirectly, where deepening of nearshore water by tidal scour permits stronger wave action to attack the shore, or where nearshore tidal deposition of sediment weakens wave attack and augments shore accretion. These effects can be seen around the entrance to Corner Inlet, and alongside the channels between the sandy islands to the east (Plate 3).

Other processes influencing coastal evolution include wind action which, in addition to generating waves, acts as an agent of deflation of sand from beaches and cliff faces, and has built and shaped coastal dune formations. Apart from studies of dune orientation in relation to onshore wind resultants (Teh Tiong Sa 1973, Bird 1978), little attention has been given to the effects of variations of wind regime and wind energy along the coast, notably between sectors exposed to the prevailing westerlies and sectors that face in other directions.

SEA LEVEL CHANGES

Considerable attention has been given to the problem of establishing the late Quaternary sequence of changes of sea level relative to land in Victoria (e.g. Gill 1961, 1971a, b, 1972c, 1973a, b, c; Gill & Hopley 1972). There is evidence that the sea stood about 7.5 m above its present level in western Victoria some 125 000 years ago, and

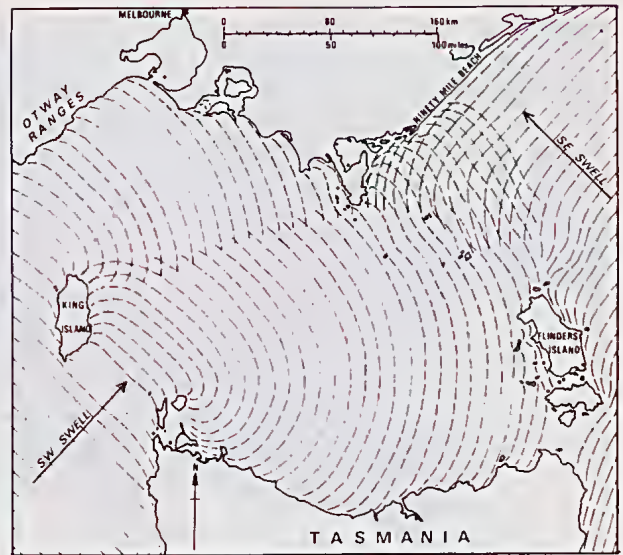


FIG. 3—Predominant ocean swell patterns in Bass Strait

about 4 m above present level 110 000 years ago (Gill & Amin 1975). There followed a long episode of low sea level correlated with the Last Glacial phase of the Pleistocene, evidence from other areas indicating that the sea fell at least 100 m, and possibly as much as 140 m below its present level 20 000 years ago. The ensuing phase of climatic amelioration and world deglaciation was marked by the Holocene marine transgression, which brought the sea up to its present level about 6 000 years ago. A number of coastal features, including emerged beaches and beach ridge systems, bluffs formed by the subaerial degradation of former sea cliffs, depositional plains that have the appearance of emerged lagoon floors, and sandy shoreline features stranded to the rear of subsequently prograded marshlands, have been taken as evidence that the sea was 2 to 3 m above its present stand between 6 000 and 4 000 years ago, and that it thereafter dropped back, yielding a 'Recent emergence'. The question of a higher Holocene sea level remains controversial, for studies on other parts of the Australian coastline, especially in New South Wales, have failed to substantiate it (e.g. Thom *et al.* 1972). Some of the emerged features on the Victorian coast could be of Pleistocene rather than Holocene age; of the order of 100 000 years old instead of less than 6 000. Alternatively the appearance of emergence could be misleading, the Holocene features having developed as the result of depositional processes with the sea at its present level. If they are emergent features they could be due to localised uplift of land during the past 6 000 years rather than a fall of sea level.



PLATE I

High wave energy coast at London Bridge, near Port Campbell (N. Rosengren, April 1976)

Attempts to correlate the evidence of former sea levels along the Victorian coast are thus complicated by the question of whether the land margin has been tectonically stable in late Quaternary times. Continuation of vulcanicity into the Holocene in the Tower Hill region and the recur-

rence of earthquake activity along Selwyn's Fault on the Mornington Peninsula are among the phenomena which make the assumption of tectonic stability doubtful: Victoria has had a long history of tectonic deformation transverse to the present coastline. Moreover, there is the possi-

bility of a differential hydro-isostatic response of the shelf and coastal margin to increasing water load as the sea rose between 20 000 and 6 000 years ago. There are contrasts in the width and gradient of the shelf off the Victorian coastline (Fig. 4), and in its structural composition. There may also have been lateral variations in its resilience and hence in its response to hydro-isostatic loading. If this is the case, the sequence of sea level changes relative to the land will be different at various points along the Victorian coastline. Clearly, much more research is needed to establish sea level sequences, and as this proceeds it will be useful to map the lateral extent of the various emerged shoreline features, and to provide geomorphological explanations for their absence from intervening sectors.

CLIFFS AND SHORE PLATFORMS

High sectors of the Victorian coast show a variety of transverse profiles, related primarily to the type and structure of outcropping rock formations and the degree of exposure to strong wave action (Hills 1971). Within granitic sectors, for example, the hard, massive granite of Wilson's Promontory shows steep rocky coasts plunging into deep water close inshore, whereas the intricately jointed granite of Cape Woolamai has been cut back into vertical cliffs behind segments of abraded shore platform, particularly on the more exposed western side, the eastern flank showing gentler coastal slopes without such platforms. In East Gippsland the granitic capes have an irregular shore topography, with only limited cliffing.

Similar variations can be traced within basalt coasts, and on sedimentary formations such as the Cretaceous sandstones and mudstones of the Otways and South Gippsland coasts (Gill 1967b, 1977), the Pleistocene dune calcarenites of the Warrnambool District (Gill 1943), Point Lonsdale (Gill 1948), and the Nepean Peninsula (Bird 1975). On some sectors, the eroding cliffs give place laterally to coastal bluffs with a soil and vegetation mantle. These are former marine cliffs that have become subaerially degraded. Some are relics of a Pleistocene coastline, as at Two Mile Bay, near Port Campbell, where the Pleistocene bluff is fronted by a low-lying coastal terrace while adjacent sectors of the coast have been cut back into vertical retreating cliffs (Baker & Gill 1957). On other sectors the bluffs appear to have been active cliffs earlier in Holocene times, and to have become subaerially degraded either as the result of

a fall of sea level relative to the land, or the deposition of beach ridges and dunes as fronting terrain which now protects them from marine attack. This sequence may be illustrated at Rickett's Point, on the north-eastern coast of Port Phillip, and on the basalt shoreline between Flinders and Somers in Western Port (Bird 1977b).

There has been considerable discussion of the mode of origin of shore platforms on the Victorian coast, and of whether their evolution required, or could be taken as indicating, a phase of higher Holocene sea level. Shore platforms show variations related to geological features and aspect. They include seaward-sloping facets which are usually ramps formed by abrasion where waves armed with sand or gravelly debris are eroding the rocky shore near the base of the cliff. There are also almost horizontal benches, terminating with a steep drop at their seaward margins. It is acknowledged, following Hills (1949), that these latter features have been shaped primarily by weathering processes, including the disintegration of rock outcrops that occurs as the result of repeated wetting by wave splash, sea spray, or rainfall, followed by drying of the rock surface. Associated with this is the process of salt crystallisation, which is difficult to distinguish from wetting-and-drying. Coastal rock formations are also subject to solution by sea water, aerated spray, rainfall and runoff, and percolating groundwater, these effects being most marked on limestones, including Pleistocene dune calcarenites. The activities of plants and animals that inhabit these rocky shores also contribute to the physical and chemical weathering of rock surfaces. In each of these ways, rock material is decomposed or disintegrated, and can be readily swept away by waves that break across the shore platform (Bird 1974).

It is evident that these processes are effective only down to a specific level, usually slightly above mean high tide level on basalts and non-calcareous sandstones and mudstones, and a little lower on limestones and dune calcarenites. A downward limit to wetting-and-drying and salt crystallisation is set by the water table, for these processes cannot operate where the rocks are permanently saturated. Similarly, solution by spray and rainfall cannot operate below low tide level, and solution by sea water at lower levels is evidently unimportant, as are the activities of the shore organisms that occupy zones below low tide level. It has been suggested that sea water is usually saturated with dissolved carbonates, and therefore incapable of further solution of limestone or dune calcarenite,



PLATE 2

Moderate wave energy coast at Black Rock Point, Port Phillip (E. C. F. Bird, October 1975)

but this hypothesis has not been examined on the Victorian coast.

The development of almost horizontal shore platforms in the transverse profiles of basalt, sandstone, mudstone, limestone and dune calcarenite coasts in Victoria can be largely explained in terms of this inhibition of shore weathering processes at and below specific intertidal levels. In addition, as Hills (1971) noted, there is evidence that shore platforms cut in dune calcarenite have become indurated by carbonate precipitation within a horizon immediately below the platform level. As a result, the outer edge of the shore platform on the ocean coasts of the Nepean Peninsula is typically a protruding slightly hardened rock. Shore platforms cut in Tertiary sandstone at Beaumaris and Mount Eliza on the coast of Port Phillip appear to have been similarly indurated, in this case by precipitation of ferruginous compounds. Further investigation of the process of induration is needed: by impeding erosion it has led to the persistence of almost horizon-

tal shore platforms on the transverse profiles of coasts where erosional processes have otherwise prevailed.

BEACHES AND ASSOCIATED FEATURES

During late Quaternary times, large quantities of sand have been deposited to form beaches, spits, barriers and dunes on the Victorian coast. Deposition has been most extensive in Discovery Bay, Portland Bay, and Port Fairy Bay; between Torquay and Cape Schanck; near Cape Woolamai on Phillip Island; between Kilcunda and Cape Patterson; in Venus Bay; and along the Gippsland coast east of Wilson's Promontory (Fig. 1). As has been mentioned, the sand deposits west of Wilson's Promontory are predominantly calcareous, while those to the east are largely quartzose. Sand deposition has also taken place locally on the shorelines of Port Phillip, Western Port and Corner Inlet,

Sources of beach material include sand and gravel eroded from cliffs and foreshore outcrops and deposited on adjacent beaches, sandy sediment brought down from the hinterland by rivers and redistributed from river mouths, and sand carried in from the sea floor by shoreward drifting (Bird 1980). The first of these is readily demonstrable along actively-cliffed sectors of the Victorian coast, where beaches in the vicinity of cliffs of Tertiary sandstone, as on the eastern shores of Port Phillip, or cliffs cut in dune calcarenite, as in the Warrnambool district, certainly include material derived from these sources. In north-eastern Port Phillip between Brighton

and Mentone the depletion of sandy beaches in recent years has followed the artificial stabilisation of formerly eroding cliffs that maintained a sand supply (Bird 1970). Beach gravels occur locally near rock outcrops which are weathering into fragments that become worn into cobbles and pebbles by wave action (Bird 1972). Shelly beaches are also found locally, either near rocky shores or reefs which provide a habitat for shell fauna, as in Bridgewater Bay, or adjacent to biologically rich estuarine or shallow marine environments, as in parts of Western Port. On the west coast of Port Phillip shelly beaches occur where other sources of beach material are sparse on a low-lying shore that

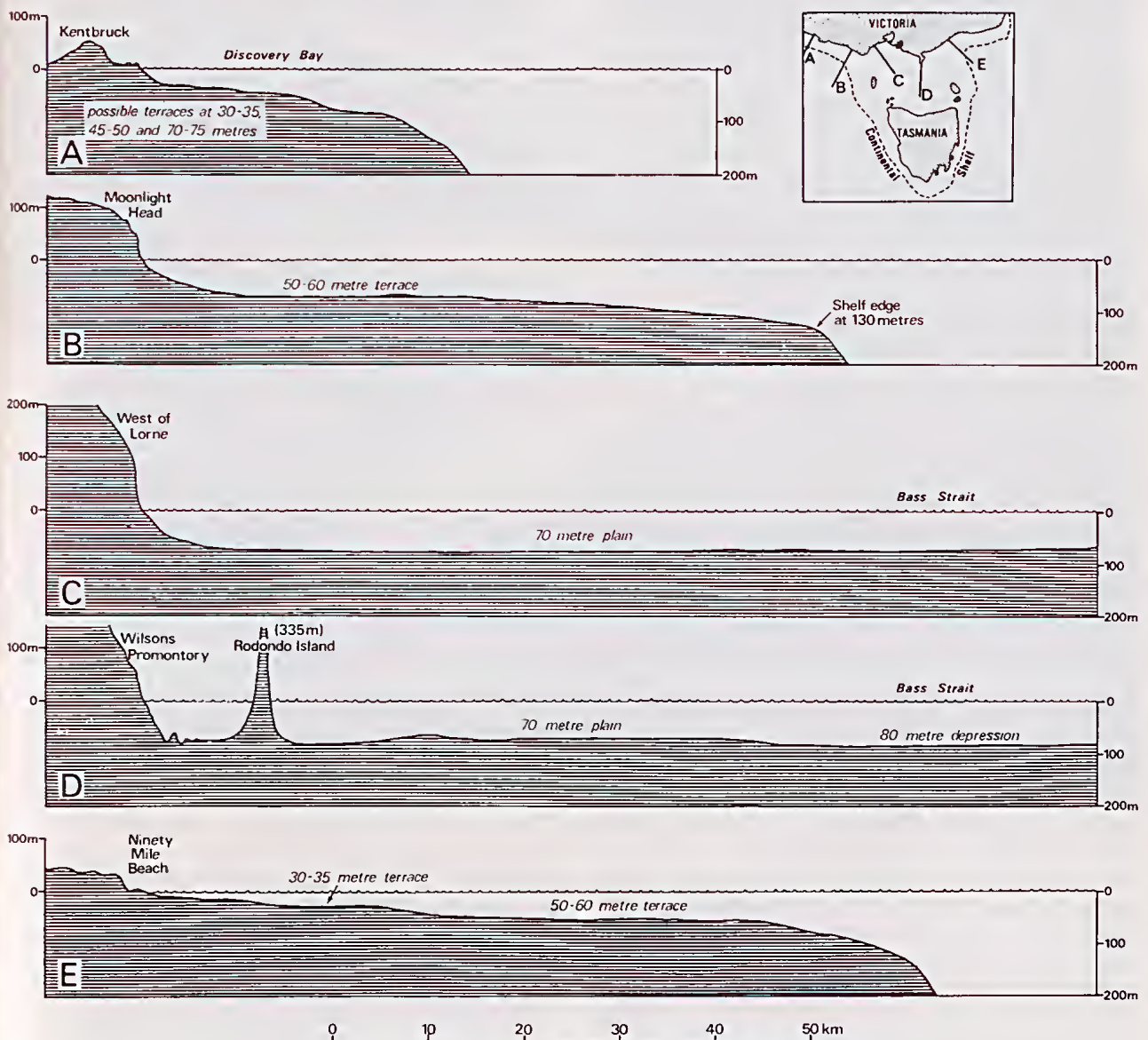


FIG. 4—Profiles of the continental shelf off Victoria

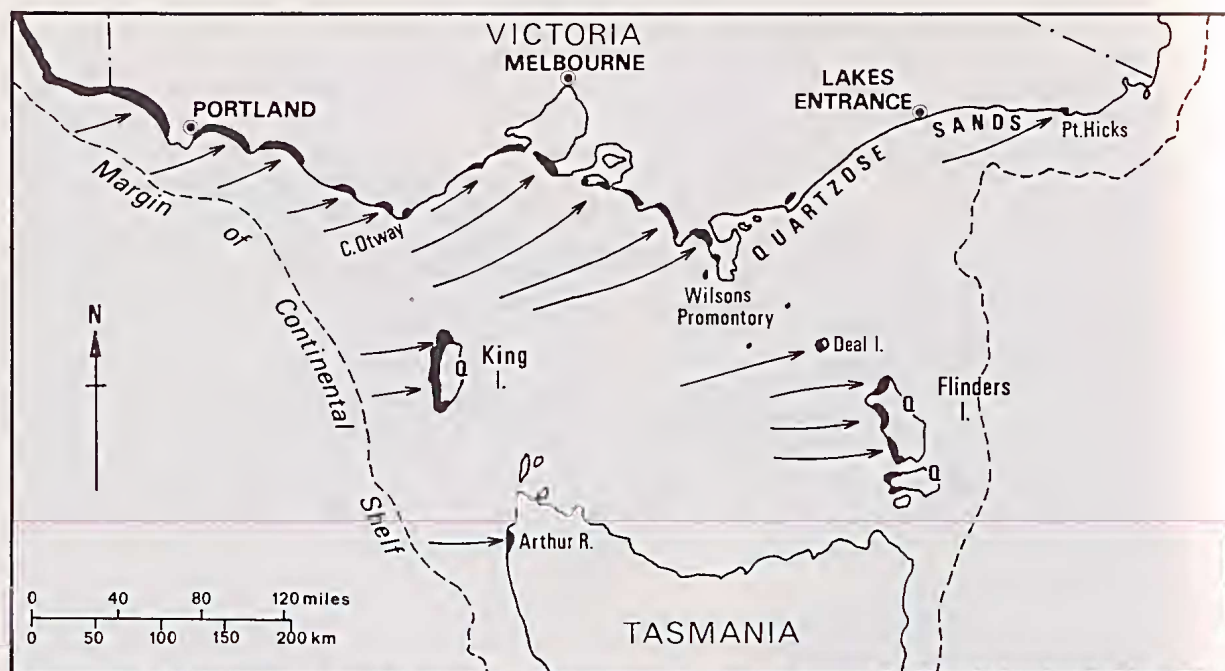


FIG. 5—Flow paths of biogenic shelf sand to calcareous beaches (shown in black)

borders weathered basaltic terrain (Gell 1978).

Sand from rivers has made only minor contributions to Victorian beach systems, because most of the rivers drain into estuarine lagoons which intercept sandy sediment before it reaches the sea. Thus sand from the Mitchell and Avon Rivers is being deposited in the Gippsland Lakes rather than on the Ninety Mile Beach. Some fluvial sand is nevertheless carried into the sea by the Snowy River during episodes of flooding, deposition by this river having largely filled the estuarine lagoons that formerly existed at its mouth. In the winter floods of 1978 sand swept out of the mouth of Merriman's Creek was subsequently added to the adjacent Ninety Mile Beach.

The development of the sandy barrier behind the Ninety Mile Beach on the Gippsland coast can only be explained by shoreward drifting of sand from the sea floor. Although it incorporates fragments of Pleistocene barriers, this outer barrier is essentially a Holocene formation, initiated when the marine transgression brought the sea to its present level, and subsequently prograded. The deposited sand cannot have come either from cliff erosion, for the only cliffed sector is the minor promontory of Red Bluff at the eastern end of the Ninety Mile Beach, or from fluvial supply, since the hinterland rivers drain into lagoons landward of the barrier. Instead, sand has moved in from the sea floor, where relics of Pleistocene beaches,

barriers and dunes stranded during the preceding phase of falling sea level, together with sediment deposited on the emerged sea floor by rivers and wind action, and sandy material produced by the weathering of shelf outcrops, were re-worked, collected, and carried shoreward by wave action during the Holocene marine transgression, and deposited to prograde the barrier shoreline (with successive beach and dune ridges) after that transgression came to an end. The process of landward sweeping would have been aided by stillstands or minor episodes of emergence as the Holocene transgression proceeded, and an emergence following a higher Holocene sea level episode would help to explain the subsequent progradation of the outer barrier; but this is not essential. Given an abundant sand supply, the barrier shoreline could have prograded with the sea at its present level, and parts of the barrier islands off Port Albert are indeed still prograding as waves move sand in from shoals on the adjacent sea floor. Along the Ninety Mile Beach, however, this progradation has come to an end, and in recent decades the shoreline has been receding as sand is lost offshore and alongshore. Erosion on sandy shorelines in Victoria has been discussed in a previous paper (Bird 1980).

Shoreward transportation of sand has also contributed beach material to other parts of the Victorian coast, the quantities delivered being related



PLATE 3

Tidal inlets between sandy barrier islands off Port Albert in South Gippsland (N. Rosengren, March 1976)

to the pre-existing topography and sediment mantle of the adjacent shelf. The relatively steep narrow shelf off the Western District would be unlikely to have provided as abundant a sand supply as a broad and gentle shelf of the kind off the Ninety Mile Beach (Fig. 4), so that the pattern of

Holocene deposition in the Port Fairy District has differed from that of the Gippsland coast. Each coastal sector has a 'shelf catchment' determining the extent to which sediment has been carried on-shore. The dichotomy between calcareous sands on the coast west of Wilson's Promontory and

quartzose sands to the east can be explained in terms of derivation from contrasted sea floor catchments during successive sea level oscillations, the largely biogenic calcareous sands having come from shelf areas to the west, where the sediment mantle is calcareous (Fig. 5), while the quartzose sands came from the granitic province associated with the shelf to the east.

The pattern of deposition of sand carried shoreward depends also on coastal configuration in relation to predominant wave regimes. Beach sand drifts along the shore where waves arrive at an angle, and accumulates on sectors where the waves move in to fit the shoreline. The pattern of sand deposition in Portland and Waratah Bays is the outcome of this. Alternatively, sand drifting into the mouths of inlets and embayments may accumulate in bordering spit formations, such as Sandy Point and Observation Point in Western Port.

Beach drifting continues, but although patterns of coastal sediment flow have been traced (Baker 1956, Bird 1972, Tan 1970) little is known of the quantities of beach material moved or the rate at which longshore transportation proceeds. More quantitative studies are required of the kind devised by Gill (1978) who sought to relate volumes of cliff retreat to volumes of sand deposition on the Port Fairy coast, and Riedel & Fidge (1977) who attempted to calculate the rate of movement of sand along the shore from Point Lonsdale to the compound spit formation at Swan Island in the south-west of Port Phillip.

Where dune topography has developed behind sandy beaches it consists either of successions of foredunes parallel to the shoreline and largely held in place by a vegetation cover, or more complex transgressive dunes, including blowouts, parabolic dunes, and sand lobes that have moved inland, some now fixed by vegetation, others unvegetated and mobile (Plate 4). Parallel foredunes are best displayed behind the Ninety Mile Beach and towards the more sheltered western ends of embayments such as Portland and Waratah Bays. On the more exposed parts of these embayments, and along the coast east of the Ninety Mile Beach, parallel foredunes give place laterally to more irregular transgressive dune formations, many of which are active, driven by the prevailing south-westerly winds inland or across promontories. Burning, grazing and trampling of dune vegetation has undoubtedly initiated erosion and mobilised formerly stable dunes during the two centuries of European occupation, but in some cases instability may have originated earlier, as the

outcome of burning of vegetation by aboriginal tribes. Older parabolic dunes now stabilised by vegetation indicate still earlier phases of natural instability, when the vegetation cover was weakened by aridity or natural bushfires, when the seaward margins were undercut by storm waves or rising seas, or when onshore winds were stronger than they are now. Where the sands are calcareous, secondary carbonate cementation has preserved overlapping Pleistocene dune formations, indicative of a long history of alternating natural stability and instability, as dune calcarenites, the seaward margins of which have been cut back as rugged cliffs on the Nepean ocean coast. Quartzose dune sands do not become lithified in this way, and the Pleistocene coastal dune topography of East Gippsland has been more readily eroded and redistributed than the dune calcarenites of equivalent age farther west.

Rates of movement of mobile dunes measured behind Discovery Bay have been up to 2 m per year, and in East Gippsland have been up to 13 m per year (Rosengren 1978), much of the advance occurring during episodes of strong wind action, especially in winter. More detailed investigations are in progress which should elucidate patterns of sand movement on mobile dunes in relation to local wind action and the effects of wetting of surface sand by rainfall, which is thought to inhibit deflation. Vegetation which traps and stabilises dune sand on the Victorian coast includes the grasses *Spinifex hirsutus*, *Festuca littoralis*, and the introduced *Ammophila arenaria*, as well as such shrubs as *Cakile maritima*. Attempts to stabilise dunes by planting such vegetation have been more successful in wet years, when rainfall has stimulated the growth and spread of these grasses and shrubs.

INLETS, ESTUARIES AND LAGOONS

The Holocene marine transgression established a number of valley-mouth inlets, as well as larger embayments such as Port Phillip, Western Port, and Corner Inlet, which owe their outlines partly to tectonic movements that continued into Quaternary times. Most inlets and estuaries are encumbered by sand deposition in and around their mouths, with shallow thresholds where sand has been washed in from the sea, usually flanked by spits surmounted by dune topography (Bird 1967). Such features are seen at the entrance to Mallacoota Inlet, an intricately branched ria formed by marine submergence of the mouth of Genoa River and its tributaries. Other inlets, such



PLATE 4

Transgressive dunes on the isthmus at Cape Woolamai (N. Rosengren, March 1976)

as Lake Tyers, are subject to phases of complete enclosure when sand barriers are built up across their mouths, reopening when these are overwashed and breached during the floods that result from occasional episodes of heavy rainfall. Anderson's Inlet, at the mouth of Tarwin River, is

a funnel-shaped estuary with a sandy threshold and bordering spits, and extensive areas of intertidal sand and mudflats, partly occupied by mangrove swamps and salt marshes dominated by introduced *Spartina* species (Boston 1973).

In western Victoria the Glenelg opens into an

estuary fringed by salt marshes and bordered by ridges of calcareous sand and dune calcarenite, and there are minor estuaries at the mouths of the Surry and Fitzroy Rivers, and more extensive lagoons such as Lake Yambuk, fed by the Eumeralla and Shaw, Belfast Lough fed by the Moyne, and Curdie's Inlet. The Barwon River flows through a freshwater swamp area before entering shallow Lake Connewarre, from which a winding tidal channel, fringed by mangroves and salt marsh, leads to the sea across a sandy spit-fringed threshold at Barwon Heads. In South Gippsland, Shallow Inlet is a broad lagoon fed only by small freshwater streams, with a winding outlet across a sandy threshold.

The most complex estuarine lagoon system is the Gippsland Lakes, fed by the Latrobe, Avon, Mitchell, Nicholson and Tambo Rivers and some smaller streams, and separated from the sea by a succession of Pleistocene and Holocene barriers. Its shorelines are partly sandy and partly swamp-fringed, the fresher areas towards river mouths bordered by *Phragmites* swamp while the more brackish areas towards the artificial entrance (opened in 1889) have salt marsh. The evolution of this extensive lagoon system has been discussed by Bird (1978), and its ecology and hydrodynamics are the subject of further investigations by the Environmental Studies Section of the Ministry for Conservation.

There is a need for more detailed studies of the various inlets, estuaries and lagoons along the Victorian coast as a basis for geomorphological, hydrological and ecological comparisons, and as a means of identifying the factors that should be taken into account in devising the management of these systems as water and wetland resources with associated fisheries and wildlife, scenic values, and recreational opportunities.

CONCLUSION

Geomorphological studies on the coast of Victoria have reached a transitional stage, the phase of description and analysis of coastal features and changes in progress giving place to more quantitative assessments of the dynamic relationships between process and form based on detailed studies of selected coastal sectors. The already substantial geomorphological literature provides a background for the selection of these sectors and the pursuit of quantitative studies.

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